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Computational study of a turbulent gas-solid confined jet flow

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ABSTRACT

In the present work, numerical simulation of a confined two-phase particulate jet emanating from a circular nozzle has been performed using Euler-Euler approach and incorporating four-way coupling. The effects of particle size (in the range 50–200 μm) and solid loading ratio (in the range 1–5) on the gas phase flow field as well as turbulence have been studied at different co-flow velocities (i.e. 2 m/s, 5 m/s and 10 m/s). It has been observed that the particles have a strong effect on the flow field and the turbulence of the gas phase. As a consequence, gas phase velocity decay rate has been reduced along the center line, and turbulence has been attenuated in the near field region due to the presence of the particles. For a single-phase confined jet, the radial velocity decay is observed in the near-field region ($X/D<10$). In the presence of a co-flow, the radial velocity has increased beyond $X/D=10$. In the two-phase jet, the gas phase velocity is decayed in the radial direction throughout the domain. Also, jet half width is reduced with decreasing particle diameter and increasing solid loading ratio (SLR).

1. Introduction

Confined jets have been deployed in various engineering processes such as injection of fuel into a combustion chamber, chemical reaction and pneumatic conveying of gas-solid flow. In some applications, these jets have been used with or without a co-flow. A co-flow has always been used to achieve a better performance by controlling the main jet. The turbulent two-phase (gas-solid) confined jets with a co-flow have been used in the pulverized coal combustion process, where the central jet containing the mixture of air and fine coal particles is surrounded by a secondary air jet co-flow. The quantity of solid particles added to the gas flow has a significant effect on the dynamics of the flow and turbulence. Therefore, it is imperative to study the interaction of the solid particles with the carrier phase in order to understand the fluid dynamics of the gas-solid flows. In the present study, numerical simulations have been performed for a confined turbulent jet with a dilute particle loading in the presence of a co-flow.

In the past, experimental and computational studies have been carried out by many researchers [1–5] for single-phase turbulent jets with or without a co-flow. The prediction of various important parameters such as the jet spreading, half-width, centerline velocity-decay rate, self-similarity behavior and turbulent kinetic energy are well established in open literature for a single phase jet. These parameters help in understanding the relevant physics of entrainment and mixing characteristics of jets, which are of primary importance in most of the practical applications. A considerable amount of research has been carried out on two-phase free jets (i.e. gas-solid jets or particulate jets). Modaress et al. [6] used laser Doppler anemometry (LDA) to investigate the particulate circular jet. They reported that the carrier phase velocity fluctuation is reduced due to the addition of the solid particles into a single-phase jet. The spreading rate of a two-phase coaxial jet is smaller than that of a single phase jet as has been demonstrated by Fan et al. [7] in their experimental investigation of a two-phase jet.

Moreover, the spreading rate is reduced with the solid loading ratio (SLR). SLR is defined as the ratio of mass flow rate of solid phase to the mass flow rate of gas phase. A two-phase jet has been investigated experimentally by Fleckhaus et al. [8] using Laser Doppler anemometry (LDA). They observed that the centerline air velocity in a two-phase jet declines less than a single-phase jet. For a two-phase jet, the smaller spreading rate has also been reported by them, which agree well with the previous study [7]. At a constant particulate loading, this effect is further intensified when smaller particles are used. Uchiyama and Naruse [9], and Uchiyama and Fukase [10] performed numerical simulations on a three-dimensional air jet loaded with spherical glass particles. It has been shown by them that the carrier phase (i.e., air) turbulence is modulated due to the presence of the solids particles. The degree of turbulence modulation is dependent on the solid loading ratio.

Liu et al. [11,12] carried out an experimental study on a two-phase granular jet. It has been observed by them that the two-phase jet is dispersed in a similar way as a liquid jet is broken up in the presence of an annular air. Also, they reported that the velocity of co-flow air

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and mass flux of the particles have a significant effects on the dispersion length of a two-phase jet. Three different dispersion modes (i.e., shear, wave and oscillating dispersions) have been identified by them. These modes are differentiated based on the Strouhal number, which has been considered as important parameter in a particulate jet. Recently, a numerical study on a two-phase jet has been carried out by Patro and Dash [13] using the Euler-Euler two-phase model, and incorporating a two-way coupling for the particle and air phases. Although their study provided valuable information on a two-phase jet, the effect of inter-particle collisions has been neglected in the particle size of 30–200 μm, and the loading ratio of 1 to 5. For a free jet with small particle loading, the collision and the sliding of the solid particles are rarely seen due to the absence of solid wall. However, the effect of the inter-particle collisions is always taken into consideration for a confined jet. The inter-particle and particle-wall collisions are seen in a confined jet due to the presence of a confining wall. In a confined two-phase jet, even at a low volume fraction (i.e. of the order of 10^{-4}) of particles, the inter-particle collisions have significant effects on the dispersion of particles in radial and axial directions [14,15]. Moreover, the sliding of the particles on the wall further complicates the numerical modeling of a confined two-phase jet. A very few literature have been available on the experimental and numerical investigations on confined two-phase jets with a co-flow. For a two-phase confined jet at a low gas density and particle velocity, a rapid mixing rate is achieved as has been reported by Hedmen and Smoot [16] in their experimental study. The mixing mechanism in ram combustor has been studied by Levy and Albagli [17] using a gas-solid confined jet. They observed that a longer combustor is required for a complete mixing of the gas and solid phases. A numerical investigation has been carried out by de Azevedo and Pereira [18] for a free as well as confined particulate jet employing the Euler-Lagrangian model with k-ε turbulence model. The effect of the restitution coefficient on the statistical distribution of velocities was analyzed by them.

Due to the complexity of the two-phase turbulent jets, experimental predictions over a wide range of particle sizes and solid loading ratios are definitely a tedious task. The availability of high speed computers and numerical models make this task little easier. Therefore, an extensive numerical study has been carried out for a two-phase confined jet to investigate the modulation of flow structures and turbulence by adding solid particles into the carrier phase (i.e., air). As has been mentioned earlier, the inter-particle and particle-wall collisions may not be neglected in a two-phase confined jet. Therefore, a four-way (particle-particle and particle-wall) coupling using Euler-Euler model has been performed in the present numerical investigation. The solid loading ratio has been varied in the range of 1–5. The effects of particle size (50–200 μm), co-flow velocity (2–10 m/s) and solid loading ratio on the turbulence, axial and radial spreading of the jet have been discussed. The particle density and air density were kept constant at 2500 kg/m^3 and 1.225 kg/m^3, respectively.

2. Jet configuration

The flow field around the confined two-phase jet along with the co-flow is shown in Fig. 1.The air and solid particle mixture is emanated from the exit of a circular nozzle of diameter, $D=13$ mm. This mixture is allowed to flow vertically downward direction into a pipe of diameter, $D_1=60$ mm and length, $L=520$ mm, respectively. The central jet with mean flow velocity of gas phase, $U_m=20$ m/s is associated with a co-flow. In the present study, three different co-flow velocities (i.e. 2 m/s, 5 m/s and 10 m/s) have been used. It is worth to mention here that the uniform velocity profiles have been used to specify the co-flow velocity. A fully developed gas-solid mixture is issued from the nozzle exit, and enters the computational domain along with the co-flow as shown in Fig. 1. The gas-solid two phase flow in a vertical downward pipe has been studied extensively by Patro and Dash [13]. They proposed different equations to specify the fully developed velocity profiles for the gas and solid phases. These equations have been implemented in the present study to specify the velocity profiles for the central jet, and are given as follows:

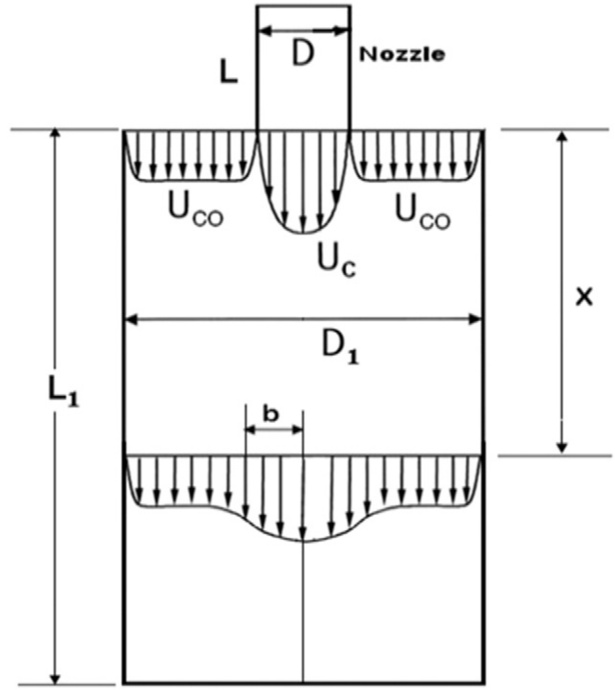

Fig. 1. Flow field around the confined jet.

$$U_g(r) = U_{gc}\left(1-\frac{r}{R}\right)^{0.14} \tag{1}$$

$$U_s(r) = U_{sc}\left(1-\frac{r}{R}\right)^{0.12} \tag{2}$$

$$U_{gc} = 1.12U_m + 0.65 \tag{3}$$

$$U_{sc} = 1.083U_m + 1.113. \tag{4}$$

3. Mathematical model

In this work, the two-fluid or Euler-Euler approach has been implemented to model the gas-solid mixture. In this approach, different phases (here, the gas and solid particles) are considered as interpenetrating continua, and thus, both the phases are treated as continuum. Therefore, the Reynolds averaged Navier-Stokes (RANS) for both the phases are solved iteratively using finite volume method by incorporating the appropriate numerical boundary conditions (discussed in Section 4). The conservation equations for each phase have been solved, and the sum of the volume fractions of both the phases is equal to one. As discussed earlier, a four-way coupling has been recommended to model the confined flow. In the four-way coupling, the particulate phase is influenced by the gas phase through the drag and turbulence. Similarly, the gas phase is also influenced by the solid phase via the reduction in the mean velocity and turbulence. Therefore, the interaction terms like drag force, inter-particle collisions, particle-wall collision have been modeled. Kinetic theory of granular flows (KTGF) is implemented for the closure of solid phase stresses and pressure,